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Ultrahigh Capacity Optical Communications beyond Pb/s

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Abstract: Recent progress in ultrahigh capacity optical communication technologies based on space-division multiplexing is described including one Pb/s transmission in a newly developed multi-core fiber with future perspectives for more capacity.
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1. Introduction

The global data traffic is continuing to increase driven by the ever-increasing computing powers, memory capacity as well as large user applications, and rapidly-increasing wired/wireless access speeds. As we look back on the last three decades since 80's, we have enjoyed various great inventions as shown in Fig. 1, achieving a capacity increase of as much as 60 dB from 100 Mb/s up to 100 Tb/s (2dB/year), and we will probably need a similar scalability for the next three decades. Recent experimental and theoretical studies, however, strongly suggest that we are approaching a fundamental capacity limit in single-mode fibers due to fiber nonlinearities, optical amplifier bandwidth, and fiber fuse [1-3]. Space-division multiplexing (SDM) to utilize the last degree of freedom of "space", initially proposed more than three decades ago [4-5], has revived and has been intensively studied recently as a means to substantially increase the transmission capacity per fiber [6-7] in a cost-effective and energy-efficient way.

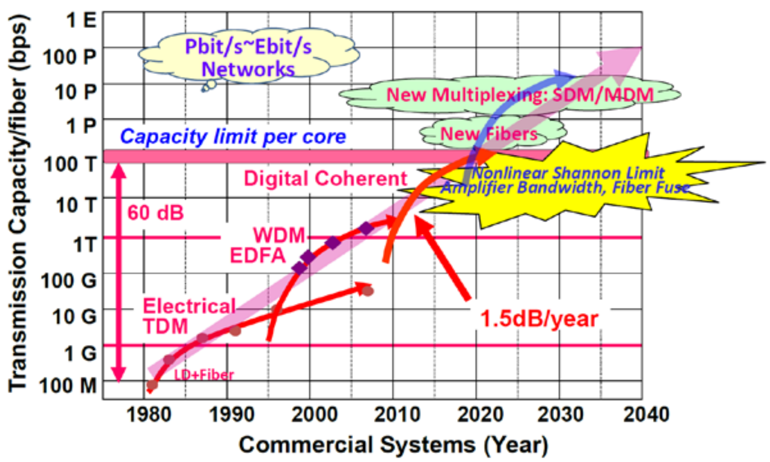

Fig. 1. Evolution of optical transmission technologies.

2. Recent progress in ultrahigh capacity optical communications technologies based on SDM

Two SDM schemes based on multi-core fibers (MCFs) [8-10] and multi-mode (few-mode) fibers (MMFs or FMFs) [11-12] have been proposed. When multiple independent modes are used as an independent channel, the multiplexing scheme is also called mode-division multiplexing (MDM). Recently, few-mode multi-core fibers (FM-MCFs) have also been proposed combining the two fibers to further increase the transmission capacity. As shown in Fig. 2, new components for SDM are space-multiplexer (SDM-MUX) to couple light from different cores or different modes into SDM fibers, SDM fibers, SDM optical amplifiers to amplify SDM signals, space-demultiplexer (SDM-DEMUX), optical connectors, mode exciters (generators) in the case of MDM, and MIMO processing. Major important characteristics of the passive components are low insertion loss, low core/mode dependent loss, low crosstalk among modes/cores and wide bandwidth to support WDM/SDM signals. SDM optical amplifiers are also a challenge where low core/mode/wavelength dependent, wide bandwidth amplification characteristics with high gain and low noise figures (NFs) are desirable in a energy efficient manner. Much progress has been made in MDM transmission, employing well designed FMFs or coupled MCFs either with or without multiple-input multiple-output (MIMO) processing, in which a transmission distance up to 4,200 km [13] or 57.6 Tb/s net capacity over 119 km [14] have been reported. MDM experiment based on orbital angular momentum (OAM) modes has also been demonstrated where 400 Gb/s QPSK data was transmitted recently over 1.1 km [15].

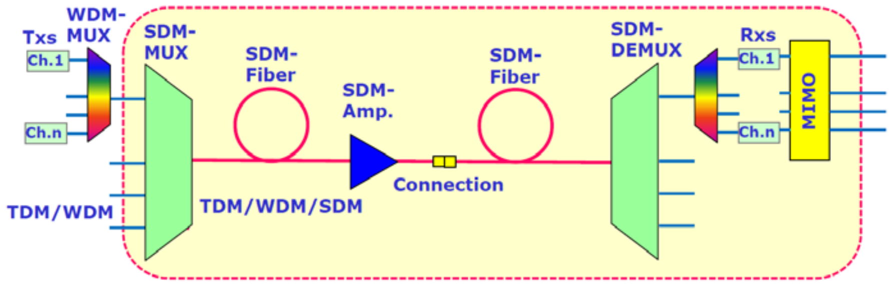

Fig. 2. Basic components of SDM systems.

SDM transmission utilizing low crosstalk MCFs has also seen many experimental demonstrations with capacity over 100 Tb/s, 300 Tb/s up to 1 Pb/s, employing uncoupled 7-core, 19-core, and 12-core MCFs [16], respectively or over 1,000 km. Multi-mode (MM) or multi-core (MC) optical amplifiers are strongly required for long-haul systems and should be major enablers to make SDM systems cost-effective and energy-efficient compared to present systems. MM or MC amplifiers, either EDFA-based or Raman-based, have been proposed and used in the transmission experiments. Nonlinearity in these new fibers has also begun to be studied [17]. Recently, one Pb/s transmission (12 SDM x 222 WDM x 456 Gb/s) over 52 km with an aggregate spectral efficiency of 91.4 b/s/Hz has been demonstrated employing a low crosstalk, a one-ring structured 12-core MCF and PDM-32 QAM modulation where the MCF has a core pitch of 37 μm, a cladding diameter of 225 μm, and the effective core area (A_{eff}) at 1550 nm and 1625 nm are 80.7 μm^2 and 84.7 μm^2 on average, respectively [16]. Attenuation at 1550 nm and 1625 nm are 0.199 dB/km and 0.207 dB/km, respectively.

3. Future perspectives

A capacity-distance product of 1 Eb/s-km (1 Pb/s x 1,000 km, for example) will be the next mile stone in SDM transmission technologies. For a new SDM fiber to be considered for installation by network operators in the future, an SDM gain in capacity of more than 100, corresponding to 10 Pb/s per fiber should be necessary. This could be realized by a combination of > 20 cores per fiber and > 5 modes per polarization per core. Fiber nonlinearity and attenuation loss of new fibers, NFs/bandwidth of optical amplifiers will limit the WDM/SDM capacity and transmission distance. Lower nonlinearity and lower attenuation loss with a new wavelength window are what hollow core photonic bandgap fibers (PBGFs) are seeking and further progress will be expected. New node/switching architectures will also be important research subjects to fully utilize the vast capacity in future networks.

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